



Leong, SC., Lee, BS., Nix, AR., & Strauch, P. (2004). A 3D pyramid network for short ranged high data rate communications at 60 GHz. *IEEE 59th Vehicular Technology Conference, 2004 (VTC 2004-Spring)*, 1, 234 - 238. <https://doi.org/10.1109/VETECS.2004.1387949>

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[10.1109/VETECS.2004.1387949](https://doi.org/10.1109/VETECS.2004.1387949)

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A 3D Pyramid Network for Short Ranged High Data Rate Communications at 60GHz

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Abstract— At millimeter-wave frequencies, the propagation characteristics approximate to that of light and high attenuation is usually incurred in the presence of people and objects. For future wireless personal/local area network (WPAN or WLAN respectively) applications, the user is expected to have maximum mobility, but the impact of shadowing is significant at these high frequencies. To mitigate such effects, a network infrastructure in the form of a 3D pyramid is proposed. It consists of a single access point with a number of active relays operating in parallel. Recent advances in radio over fiber allow such technique to be used between the relays and the access point. Simulations are performed in a sophisticated 3D ray tracing tool. Human figures are added with shadowing densities of 1 person/256m² (total room area) up to 1 person/1m². Simulated results show that comparing to a normal system with just a single access point either mounted on the ceiling or at the same height as a mobile terminal; the pyramid relaying system provides superior coverage and capacity.

Keywords—component; 60GHz, relay, pyramid, WPAN, WLAN

I. INTRODUCTION

Millimeter-wave (mmW) radio has the potential for data transmissions in the order of Gbps. Future wireless devices may see a seamless unification of heterogeneous devices such that the demand for large bandwidths is highly justifiable. To meet the ever increasing demand for bandwidth now and in the future, the US has allocated 7GHz at mmW band from 57-64GHz for ISM use. Internationally, this band has also been allocated to around 5GHz of license exempted operation.

To date, most literature focuses on highly directive point-to-point links for mmW communications in order to combat the high attenuation property inherent at high frequencies, especially at 60GHz. Such links poses difficulties for WPAN/WLAN. For instance, the user's mobility becomes severely limited. The effective coverage distance for high data rate is reported to be within the boundaries of WPAN (20m) [1]. Due to this inherent property, the impact of object and human body shadowing becomes difficult to be ignored. It is reported in [2] that body attenuation can be as high as 18dB or higher.

In this paper, *Section II* describes our proposed system to combat severe shadowing problems at 60GHz. *Section III*

describes our simulation objectives, strategies and methods. This section also defines the basic assumptions used for the various system models. In *section IV*, results produced by the models are discussed. Finally *section V* gives the conclusion of this work.

II. SYSTEM MODEL

The performance of mmW systems cannot be justified merely by having good BER performance. New ways has to be developed to study and overcome the effect of shadowing while taking advantage of its high frequency reuse property and its very large bandwidth. The proposed system here employs a blanket coverage strategy to combat high attenuations from human and object shadowing with the assistance of active or passive relays.

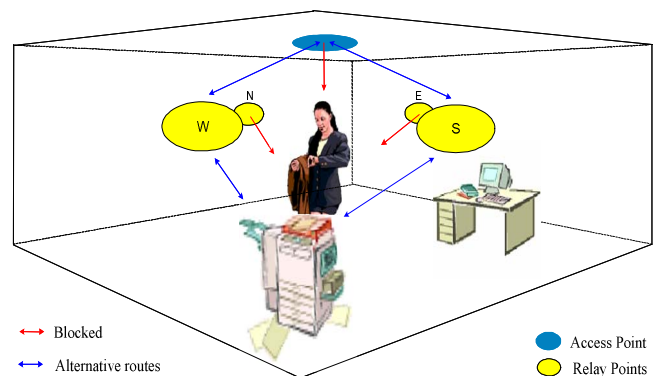


Figure1. Application example using the WPAN pyramid network at 60GHz

In **Figure 1**, line-of-sight (LoS) paths between the mobile station (MS), printer in this case and the access point (AP) are blocked by a person. Alternative routes may then be set up from the west (W) or south (S) relay points (RP). The RPs are arranged such that they form the base of a pyramid structure and with the AP itself as the apex of the pyramid. Please note that the structure is not limited to 4 RPs; it depends on the extent of coverage needed by the user as well as the dimensions of the room.

Such an infrastructure giving coverage in all directions grants the user maximum freedom of movement, especially for

high speed WLAN and body worn WPAN devices. In addition, it simplifies the RF front end and power requirements of these mobile terminals since most complexities are built into the AP and the RPs. Although the figure above gives a scenario of a square room, other room sizes such as long corridors; 2 RPs may just be enough. Additional RPs can also be added to increase coverage. At a wavelength of only 5mm, it is possible that super antenna arrays to be formed in an area no larger than the surface area of a watch. This can be extremely attractive and cost effective especially if passive devices which require no power supplies are used for the RPs. On the contrary, using reflectors may be large, unsightly and even tedious to set up. With suitable antenna configurations, the shadowing problem at 60GHz may be mitigated. Notice that only one AP is required for a pyramid relay structure, eliminating the necessity of handovers.

Proposed here is a parallel relaying technique whereby each RP communicates directly with the AP and vice versa. There are two methods by which links between RPs and AP can be established. The first method employs radio over fiber [3] (RoF) for wired relaying and the second, uses directional antennas with narrow beams for wireless relaying. There are pros and cons to each method. The first being the extra costs on cable installation and RF-optical front ends. However it provides the most reliable links with minimal cable losses and path delays, as well as having maximum control since the AP may then act as the central control node in this way. The second method has more flexibility in the placement of the RPs as long as they maintain LoS with the AP at all times. In addition, relay channels with high SNR may also be established when they are mounted up high such that human and object shadowing do not occur between them. The first method utilizing RoF is considered here.

Both methods however, may be prone to heavy interference between the relays during uplink and downlink sessions. This could be mitigated by segregating the uplink and downlink frequencies with FDD and timing intervals between packets with TDD, for example. Please note that for TDD, the overall capacity of the system may be reduced due to the delayed transmissions via relayed links. Actual details on radio resource allocation are beyond the scope of this paper. Additionally, mmW dielectric lens antenna could also be used to further limit interference from the highly directive beams of other RPs in the wireless relaying case. The lens antenna operates by providing a circular uniform symmetrical power pattern throughout its coverage [4] as shown in **Figure 3**. Further more, it is also cheap and easy to fabricate.

A. Relaying strategies

Wireless relays are generally utilized in two modes: amplify-forward (AF) mode and decode-forward mode (DF) [5]. The relays may also operate in parallel [6] single-hopping or in cascaded serial multi-hopping fashion as with ad-hoc networks. The proposed pyramid system here may be classified as an infrastructure network with fixed parallel relay terminals as depicted in **Figure 2**. Here the source, s and the destination, d can either be the AP, the RP or the mobile station (MS) depending whether it is the case of an uplink or a downlink. The signal-to-noise ratios (SNR) between s - r , s - d and r - d links

are then measured before each transmission, as well as to update the entire channel condition. Various power algorithms can then be used to minimize transmission power and to maximize reception quality; however this is not the scope of this paper.

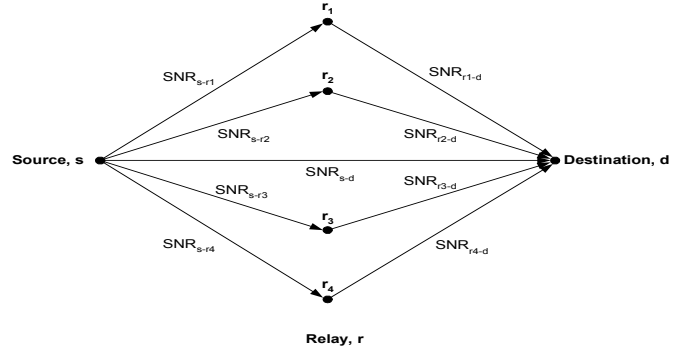


Figure 2. The pyramid parallel relay model

III. SIMULATION OBJECTIVES AND METHODS

The simulation of the pyramid network under human and object shadowing conditions is a 2 step process: deterministic and statistical. In this experiment, only the uplink is considered. Millimeter-wave dielectric lens and wide angled directional antenna patterns are used for the AP and the RPs in the pyramidal configuration. For the conventional single AP case, a vertically polarized dipole antenna pattern is used. The mobile is also assumed to have the same omni-directional pattern in all test cases. The simulation objective here is to give an idea of the pyramid system's performance as compared to conventional single AP systems. To be realistic, a fully furnished 18.7x13.7x3.8m medium sized office with actual dimensions of all objects is used. The dielectric properties of the office materials are also taken into account in the deterministic model. Please refer to **Figure 6** for the computer generated 3D model.

For the pyramid relay system, it is desirable that a uniform coverage be provided regardless of shadowing, and at the same time limiting co-channel interference between the relays to the minimum. One strategy is to use dielectric lens antenna. Another is to utilize wide angled directional antennas such as the 120° directional antenna proposed here. Since these antennas are inverted to provide coverage towards the ground, strong and highly directed rays between the relays (in the wireless relaying case) as well as strong undesired ceiling reflections are mitigated. Besides the room size, the height of the antennas is also a crucial part of the entire coverage design. Here, the AP is mounted at a height of 3.55m, the RPs at 3.0m and the MS at 0.9m.

A. Basic simulation assumptions

- The diffraction phenomenon at 60GHz is negligible and thus not taken into account.
- Ceiling, floor and walls are assumed to be smooth such that diffused indoor scatterings are not taken into account.

- Only up to second order reflections are considered since received power from higher order reflections are too small to be considered.
- Human body shadowing attenuation is set to be 18 dB as reported in [2]. The attenuation level is assumed to be constant throughout the simulated human figure.
- Oxygen absorption at 60GHz in an indoor environment is negligible.
- The distances between each RP and the BS are equal so that the link qualities of all RPs with the BS can be assumed to be consistent in all directions.
- RoF is assumed to establish links between the RPs and the BS and that the optical media is assumed to be lossless.
- The AP employs selection combining technique to select a relay branch with the strongest RSSI.
- Analysis in this paper is based on a single user environment.
- The user bandwidth is assumed to be 1GHz. Thus the noise floor is -84dBm; assuming a noise reference of -174dBm/Hz.

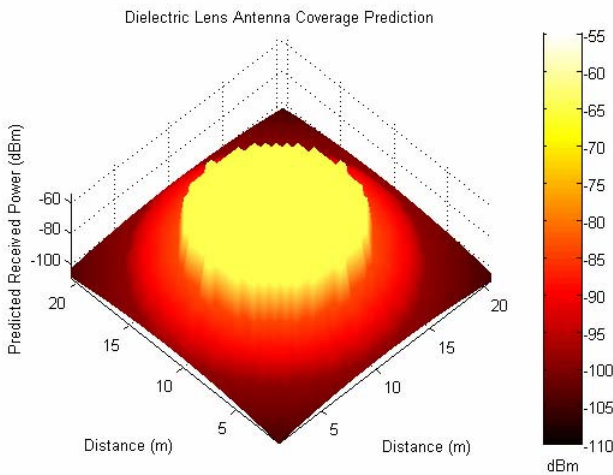


Figure 3. Predicted received power for an ideal mmW dielectric lens antenna for the AP.

Figure 3 shows the coverage estimation for an ideal mmW dielectric lens antenna with a directivity of 76° . Note that the lens's coverage boundary is pretty sharp as depicted in the above figure. Utilizing the dielectric lens antennas for the pyramid, the overall coverage prediction for an office under test determined by the deterministic model is as shown in **Figure 4**. Please refer to **Figure 6** for a 3D representation for the office.

Figure 5 depicts the power coverage of a conventional single AP mounted on the ceiling at a height of 3.55m in this case. Notice the corners in the room are not well covered even mounted up high. The second column of benches at the bottom

left, bottom right and some of the top left and right benches are severely shadowed by the partitions.

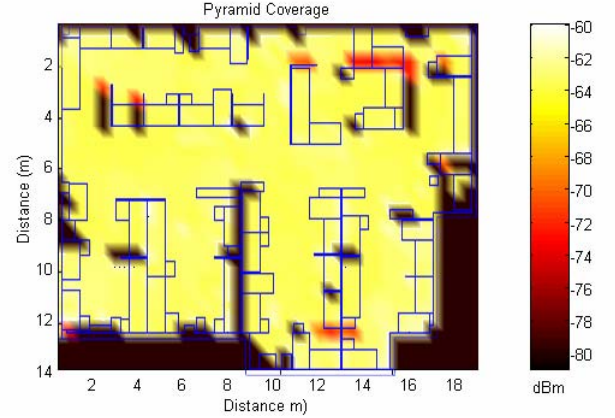


Figure 4. Coverage estimation of the pyramid relaying system.

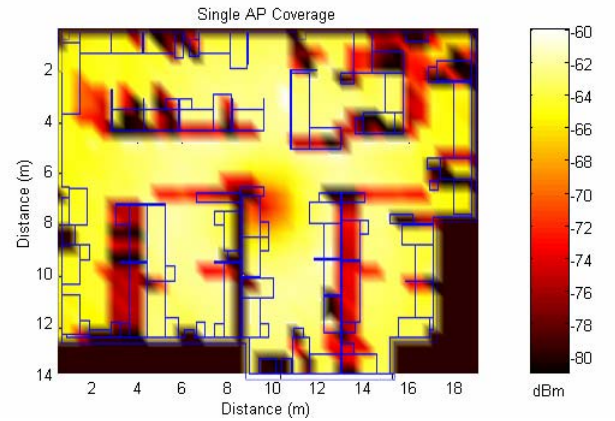


Figure 5. Coverage estimation of the conventional single AP system.

B. Human body shadowing simulation methods

To model human shadowing in specific environments, geometrical values of the rays and objects are needed. These are extracted from a highly accurate and sophisticated 3D ray tracing tool [7]. Human figures are then modeled as rectangular boxes so that various orientations can be considered. These are then placed randomly across the entire room's available space as demonstrated in **Figure 6**. To compute the interception of rays with the human figures, a 3D ray-box intersection algorithm is applied. Direct and reflected rays are attenuated as they pass through the shadowing figures. Note that a ray may be attenuated a number of times.

The number of human figures to be placed is according to a shadow density parameter specified in the simulator (1 person/ $X \text{ m}^2$, see **Figures 7 to 9**). The shadowing distribution is independent and identical (i.i.d.) so that each shadowing situation is uncorrelated with the AP and the RPs and that identical shadow positions can be reproduced for all system configurations. For each shadow density, the results are iterated for at least a thousand times and then averaged. The process is repeated for up to 22 mobile positions which are rather

uniformly distributed across the room in order to access the performance of different coverage strategies.

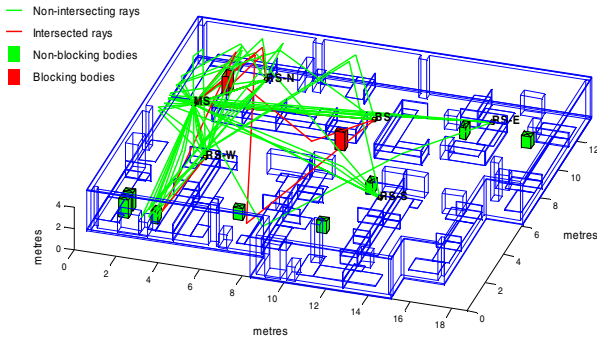


Figure 6. 3D ray tracing output for the pyramid relay system with human body shadowing

In **Figure 6**, the red or dark lines and boxes indicate that the ray paths are intersected and attenuated. To get a better representation of the presence of people in a room, the human figures are randomly assumed to be either standing (1.78m) or sitting (1.2m). Their orientation is also randomly selected either at 90 or 180 degrees to mimic that they are facing different directions at different times.

IV. RESULTS AND DISCUSSIONS

As mentioned, 22 mobile stations (MS) positions are placed rather uniformly across the room in order to get a good average of the overall system performance. Thus each point on the curves from **Figure 7** to **9** is an average value of all the 22 MS positions. Four system setup scenarios are considered: System 1 - Pyramid Lens: a pyramid system utilizing dielectric lens antennas as depicted in **Figure 3** and also **Figure 4** for the entire coverage prediction. System 2 - Pyramid Directional: a pyramid system utilizing 120° directional antennas. System 3 - AP Top: A conventional single AP with omni-directional antenna mounted on the ceiling at the center of the room. Finally, System 4 - AP Level: The same AP placed at the same height as the mobile terminal at the center of the room. In all figures, the x-axes indicate decreasing shadowing densities starting from 1person/1m² (very dense) up to 1 person/256m² (i.e. only 1 person in the entire office).

In **Figure 7**, due to the availability of alternative routes with relays from all four directions, System 1 and 2 give very low RMS delay spreads in all shadowing situations. System 3 and 4 are more dispersive at low shadowing densities, but interestingly, their RMS delay spreads improve with increasing shadow activities. The first reason is that there are fewer rays at mmW and the second reason being more rays are blocked and attenuated as shadowing activities increase. These all contribute to the decreasing RMS values. However, decreasing RMS values do not imply increasing system performance as **Figure 8** and **Figure 9** clearly show the drastic decrease in average SNRs and average system capacities.

Depicted in **Figure 8**, we can clearly see that the average SNR performance of System 3 has lowest SNRs in all situations. Specifically the SNR start to drop quickly with

shadowing densities of 1person/100m² and higher. If the same AP is mounted on the ceiling (System 4), the result is better. However the SNR starts to drop from shadowing densities of 1 person/50m² and significantly above 1 person/10m² point (towards left of axes). For System 1 & 2, their average SNRs only start to make noticeable gradual decrease from 1 person/10m² onwards.

From **Figure 9**, the mean of the average raw capacities of 22 MS positions for System 1, 2, 3 and 4 are 4.4 bps/Hz, 3.6 bps/Hz, 2.0 bps/Hz and 0.6 bps/Hz respectively. What is important is to note that in this particular office environment, System 4 fails to give any capacity output with human body densities greater than 1person/2.8m² and that System 3's overall capacity drops below 1 bps/Hz at this point. Capacities of System 1 and 2 are approximately halved to 2 bps/Hz even in the densest scenario at 1 person/1m² when compared to those at lower densities.

For power constrained systems, it is useful to note the number of bits a system can transmit for every Joule of energy. This is depicted in **Figure 9**'s y-axis on the right assuming a user is allocated with 1GHz of bandwidth when operating at 60GHz. The bits/Joule ratio can be computed with the following relation:

$$C \left[\frac{\text{bits}}{\text{sec} \cdot \text{Hz}} \right] \times B [\text{Hz}] = u \left[\frac{\text{bits}}{\text{Joule}} \right] \quad (1)$$

$$\left(P_{AP} + P_{relay} \right) \left[\frac{\text{Joule}}{\text{sec}} \right]$$

, where C is the capacity, B the bandwidth, P_{AP} and P_{relay} the AP and relay transmitted powers respectively, and u is the transmitted bits per unit energy. With this, suitable algorithms can thus be formulated to control powers at the AP and the relays to obtain the maximum number of transmitted bits with the least possible energy.

V. CONCLUSION

It can be concluded that the Pyramid systems proposed here are able to mitigate not only the effects of heavy object and human body shadowing, at the same time also able to exploit the high ISM bandwidth offered at 60GHz by maintaining high capacities and freedom of movement. Since mmW energies are largely absorb by thick partitions and concrete walls, high frequency reuse capabilities inherent at these frequencies can also be exploited. In the case of a conventional AP placed about the same height as the mobile, the overall performance is very sensitive to the transmitter-receiver distance and shadowing activities. Mounting the AP up on the ceiling gives better chances of reception; however it still fails to deliver enough capacity at high shadow densities.

With the assistance of relays strategically positioned in the form of a 3D pyramid structure, alternative paths from all directions are created. And with suitable antennas, the overall pyramid system performance remains consistently high even under severe shadowing. The type of antennas; lens or directional antennas will depend on the user's criteria; e.g. cost and/or size. From these simulations, it can be deduced that when analyzing mmW radio for WLAN and WPAN operating at 60GHz, conventional BER analyses alone are not enough to

judge the overall system performance due to its high attenuation characteristics and a rather limited number of diffused and specularly reflected scatterers. Thus objects and human shadowing have to be factored into the overall system performance equations.

ACKNOWLEDGMENT

The authors wish to extend their thanks and appreciation to Prof. J.P. McGeehan and Yukio Kamatani of Toshiba Research Europe for their sponsorship and support for this work. In addition, also thanks to all other Toshiba and university of Bristol researchers for their valuable comments and guidance.

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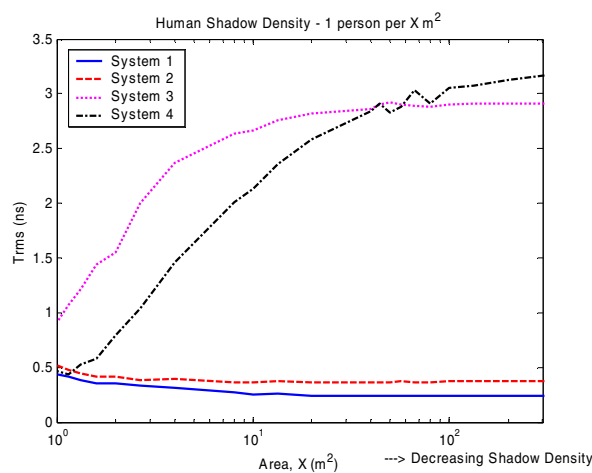


Figure 7. RMS delay spread of various system configurations

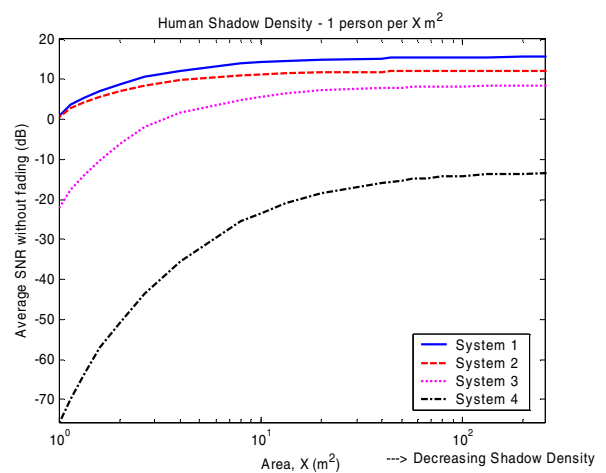


Figure 8. Average SNR of various system configurations

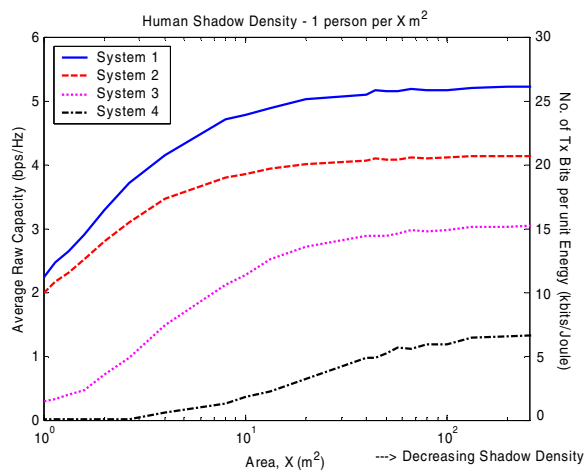


Figure 9. Average capacity and Bits per Joule analysis of various system configurations

Key

System 1: Pyramid with 76° dielectric lens antennas.

System 2: Pyramid with 120° directional antennas.

System 3: A single AP* mounted on the ceiling.

System 4: A single AP* placed at the same height as the mobile terminal*.

* - with vertically polarized omni-directional antenna.